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ABSTRACT

Researchers of problem solving in science often find themselves in the situation of studying complex problems within a scientific discipline while constrained by the necessity of studying simple, well-defined problems. They then often generalize the results to the more complex problem. In this paper, this process is explored as it applies to the study of how knowledge and skills transfer to novel problem-solving tasks. Illustrated in this paper is the point that the changing views toward transfer have been strongly influenced by the process of studying well-defined problems and the use of tested methodologies; this is accomplished by providing a selective review of the literature during the last century. The traditional problem-solving process is then evaluated in this historical perspective. Two areas of future research which may help to delineate a clearer understanding of transfer are described: transfer within domains and transfer across domains. A list of 19 references is included. (CW)

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TRANSFER PROBLEMS, LOST KEYS, AND LAMPPOSTS: A HISTORICAL PERSPECTIVE AS A GUIDE FOR FUTURE RESEARCH

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Physicists have spent much time and energy studying the hydrogen atom. Why? Because it is a relatively simple system. Only two atomic particles are involved, and their interactions can be solved exactly. Even though one might wish to know something about more complex atoms, it is wise to move from the simple to the complex. If one cannot understand the simple hydrogen atom, the complex carbon atom would be overwhelming. Studying simple systems in order to understand complex systems is somewhat like the person who is searching under a lamppost for keys that he lost down the street, because the light is better under the lamppost. Searching where the light is best has proven enormously successful for the physicists. One can understand a great deal about helium and heavier elements by considering them as perturbations and approximations of the hydrogen atom. Physicists also "idealize" other complex systems in an effort to understand them. In many instances, the simple generalizes quite well to the complex.

Researchers in science problem solving find themselves in a situation similar to that of the physicists. We wish to know about a complex process--problem solving within a scientific discipline--but we often are constrained by the necessity of studying simple, well-defined problems. We then often generalize the results to more complex problems. In this paper, I shall explore the process of "searching where the light is best" as it applies to the study of transfer of how knowledge and skills transfer to novel problem-solving tasks.

Transfer of knowledge and skills to novel situations has been an issue since the beginnings of formal education. Because one cannot learn all there is to know in a formal setting, educators hope that their students will be equipped, through formal education, with habits of mind, learning skills, or generalizable knowledge that can be applied in everyday life. Educational research, however, has not provided a definitive answer to the question of whether transfer does occur in problem-solving tasks. During the last century, the prevailing view toward transfer has changed. Currently, educational researchers lean toward the opinion that transfer does not occur, at least not in any interesting fashion. That view is undergoing modification, though.

I shall illustrate in this paper that these changing views toward transfer have been strongly influenced by the process of searching where the light is best, "good lighting" being the study of well-defined problems and the use of tested, or currently popular, methodologies. The following section contains a selective review of research results and changing views toward transfer during the last century. In this review, I claim no detailed accuracy of which results or theories influenced opinions on whether transfer occurs. The presentation of ideas is also not chronological, as differing views commonly exist in parallel. I merely ask that the reader acknowledge the plausibility of the presented arguments as a means of illustrating how changing views on transfer have come about.

Following the historical perspective, I shall address the question of whether educational researchers are always wise to follow the physicists. Are results derived from the study of simple problems generalizable to complex problems? Finally, I will describe two areas of future research that might help delineate a clearer understanding of transfer than we now have.

Changing views of transfer

The study of transfer is not new. At the turn of the century, Thorndike and Woodworth (1901) proposed a theory of "identical elements" to account for transfer of knowledge and skills to new domains. The theory suggested that subjects' success in solving problems in a new area

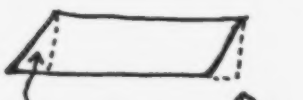
rested on the number of stimuli in the new situation that were identical to stimuli present in familiar situations. Thorndike and Woodworth found, however, little evidence that transfer of cognitive abilities actually took place on a large scale, e.g., from the study of Latin to other disciplines. Later studies, though, did find evidence of transfer in a limited sense. The problems of study that supported the view that transfer did take place were simple ones--learning word lists consisting of paired associates, for example (Ellis, 1965). Similarly, researchers defined "concepts" as a simple rule by which one might discriminate one design from others (Wittrock and Keisler, 1965). For example, a "correct concept" might be a large, round, green object. A subject who learned the correct concept would be said to have transferred knowledge to a new situation if he or she could discriminate the correct concept in a new set of stimuli. Such simple "problems" were used mainly because it was easy to study them--the stimulus features were easily identified, so that one might determine which elements were "identical" in two situations.

Given a theory of identical elements and simple, well-defined problems to study, it was logical to conclude that transfer did occur readily and could be accounted for by a reasonable theory. One could explain results of transfer experiments, provided those experiments also dealt with relatively simple problems. "Negative transfer", or incorrectly applying a rule or "concept" to a novel situation (Luchins and Luchins, 1959) and functional fixedness, or failing to see novel uses for materials in a problem-solving task (Duncker, 1945; Maier, 1931), can be explained by the large number of identical elements that invoke a familiar problem-solving procedure and thus prevent a subject from solving the novel problem.

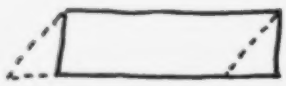
This research demonstrating that transfer occurred readily suggested (through overzealous generalizations) that transfer can take place when moving from one subject area to another, regardless of the similarity of the domains. Later research, inspired not by a theory of identical elements, but by theories of the mind as an information processing system, supported the notion that problem-solving skills transfer readily to novel tasks. Ernst and Newell (1969) and Newell and Simon (1972) developed a computer program called General Problem Solver that could apply the general skills of means-ends analysis to solve novel problems. Anzai and Simon (1979) developed a similar program. Once again, though, the problems that these computer programs were able to solve were relatively simple and "content-free," making generalization to complex problems suspect.

Gestalt psychologists began to challenge this simplistic view of transfer by proposing new, conceptually rich problems. Wertheimer (1945) proposed transfer situations similar to the following:

> A subject learns how to compute the area of a parallelogram by re-structuring the figure to a familiar one



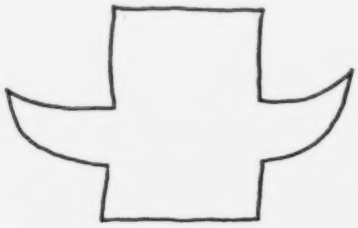
This area is identical to the "missing" area on the other side



Therefore, simply move the area to the new position, resulting in a rectangle. The area of the rectangle is easily computed.

A subject who "understands" this procedure (as opposed to having memorized an algorithm for computing the area of a parallelogram) should be able to solve the "transfer" problem of finding the area of the following figure.

Further, the subject should realize that finding the area of the following figure is impossible without further information.



It is difficult to explain this type of transfer with a theory of identical elements, in part because of the difficulty of defining elements that are common to the two situations. Although one can describe the commonality as having something to do with "missing pieces," there is a certain vagueness about that description that is problematical for predicting new results.

The early work of gestalt psychologists did little to dissuade researchers from believing in transfer of knowledge, but it paved the way for the study of conceptually rich problems. Cognitive researchers began to study more complex problems, of which problems associated with science were typical. In the tradition of studying where the light was best, researchers then (and still) focussed on well-defined, textbook problems. The results of this research (Chase and Simon, 1972; Chi, Feltovich, and Glaser, 1981; Glaser, 1984), along with emerging theories of cognitive structure (Ausubel, 1968), demonstrated the overwhelming importance of domain-specific knowledge in solving problems. It was found that, for successful problem-solving performance, general skills such as working backwards from the goal, setting subgoals, and means-ends analysis, are not as important as an integrated, hierarchically-structured knowledge base. This led to the now widely-held notion that, for practical purposes, transfer does not occur. The following example will illustrate the point.

Suppose a student learns, in his or her physics course, how to control variables--changing one variable at a time, while holding others constant, in order to determine the effect of changing that one variable on the system under study. One day this student's automobile won't start, and he or she decides to fix it. This problem-solving situation is, on the surface, quite

different from those encountered in a physics course. Our student decides, however, that in order to determine which engine component is causing the trouble, he or she must utilize the method of control of variables. The student has transferred a skill to a novel situation. But how successful will the student be in starting the car if he or she hasn't the slightest idea how an automobile engine works? The general skill of controlling variables has transferred to the new subject area, but because it will not lead to successful problem-solving performance without a thorough knowledge of the new domain, the transfer produces no interesting results. For practical purposes, it can be said that transfer has not taken place.

Because general skills are so overshadowed by domain-specific knowledge, and the domain-specific knowledge itself is usually of no use in a new subject area, researchers have recently spent little time studying transfer. In fact, we often fail to acknowledge its existence when it does occur. For example, Simon and Simon (1978) categorized the use of strategies such as working backwards from the goal as those characteristic of a novice problem solver, despite the fact that those strategies were obviously transferred from a different subject area.

Is searching where the light is best always best?

It is clear that established research practices, in the form of problems typically studied and methodologies used, color our perception of a phenomenon like transfer of knowledge and skills to novel situations. Given this perspective, we must ask if, like the physicists, we should strive to move from the simple to the complex. In going from content-free problems to problem-solving in complex domains, or from well-defined to ill-defined problems, are we on the same footing as the physicist who considers the helium atom as a perturbation of the hydrogen atom? The conflicting views of transfer that result from such generalizations suggest that we be cautious.

Educational researchers are in a difficult situation. We wish to know about very complex interactions within a student's mind, and between a student's mind and complex subject matter. In order to obtain meaningful research results, we must simplify our investigations. That simplification can take the form of well-defined problems to study, research methods that have proved successful, and controlled, laboratory settings. In this sense, we are searching where the light is best. I do not advocate that we abandon such methods, but rather that we alter them somewhat. One should not search under a lamppost if that lamppost is so far from the lost keys that the search is a waste of time. If the lamppost is relatively close to the lost keys, however, searching about in the dim light provided may prove useful. We must strike a balance between the study of well-traveled or well-defined research problems and research problems that are of practical educational concern.

In an attempt to clarify what I mean by "searching in dim light," I will describe two areas of potentially fruitful research on transfer in problem-solving. One is already being addressed in the literature and those results are contributing to a new perspective on transfer. The other breaks newer ground. First, though, I will distinguish between two types of transfer in order to guide the later discussion.

Transfer can be thought of as occurring across domains, as in going from problem solving in physics to problem solving in chemistry, or within domains, as in going from one type of physics problem to another that utilizes the same underlying physics concepts (see Figure 1). The transfer from physics to diagnosing problems with an automobile, presented earlier, is an example of the first type. Consider the following as an example of the second type.

A physics student has learned how to do Newton's Second Law problems that involve two masses, such as the one illustrated in Figure 2. The student's procedure for solving this problem is to isolate each mass separately with a free-body diagram, write $\Sigma F=ma$ for each mass, and solve the resulting equations for the tension in the rope. The student is now confronted with a new problem, illustrated in Figure 3. This problem is, on the surface, quite different from the first problem. The student recalls, however, a basic bit of knowledge about the use of Newton's Second Law: one always chooses a portion of the world to study (a "system") and applies $\Sigma F=ma$ to that system. In the first problem, one desired the tension in the rope, so one should choose a system or systems such that the tension is an external force acting on the system. Thus, on the second problem, the student defines the top three-fourths, or the bottom one-fourth, of the heavy rope as a system (see Figure 4) so that the tension three-fourths of the way down the rope will be an external force acting on the system.

Insert Figures 1,2,3, and 4 about here

Transfer within a domain might, at first glance, appear to be easier to accomplish than transfer across domains. After all, the "conceptual context" of the problem solving is similar, if not identical. In moving to a novel situation that has familiar conceptual underpinnings, though, one must transfer not only general skills, but a conceptual understanding of the subject mater. The transfer exhibited by the student solving the Newton's Second Law problems is related to the student's understanding of a basic principle (choosing an appropriate system) associated with Newton's Second Law. Therefore, because much more is expected (transfer of concepts as well as skills), transfer within domains might well be the more difficult of the two to accomplish.

That transfer within domains is difficult, and does not occur readily, is illustrated by an anecdote told by Richard Feynman (1985), in which he described to several engineering students the interesting fact that the tangent to a French Curve at its lowest point is always horizontal. The engineering students were astounded at Feynman's tremendous insight into the subtleties of a French Curve, even though this was a simple case of conceptual transfer of a basic concept in calculus. Most of us can probably think of times when we have failed to transfer knowledge within a given discipline, and we certainly know of instances when our students have failed to do so.

Future Research

Below are two examples of how researchers might investigate the transfer of knowledge and skills by searching where the light is not bright. One example deals with transfer within domains and the other transfer across domains.

Transfer within domains

With increased interest in modeling expertise and the knowledge structures of good an poor problem solvers within a subject area, surprisingly little attention is paid to what knowledge

structures are associated with the ability to do transfer problems in the domain. Expert-novice studies usually involve experts solving problem that are "typical" of the domain. A well-structured knowledge base is obviously of great importance in such a situation. There is evidence, though, that experts utilize general skills to a large extent when confronted with problems that are not of the "textbook" variety, i.e., problems that are transfer problems for the experts (Clement, in press). It is possible that we have underestimated the role of general skills in determining what facilitates transfer within a domain (Perkins and Salomon, 1989). This underestimation has come about, in part, by our reliance on the expert-novice paradigm. We have learned a great deal from this paradigm, but perhaps we should be looking in less tested waters. There is a wealth of information to be gained from studying the transfer problem-solving abilities of subjects who are all at the same level of instruction--be they experts, novices, or somewhere in between.

Research in this area would be relatively near the metaphorical lamppost. There exists a solid base of theoretical models and empirical results (Heller and Reif, 1984; Robertson, 1987) to guide the investigation of transfer within a subject area. But there are also new uses of techniques and new problems to be used in the research. Detailed examination of verbal protocols will be necessary to formulate clear pictures of the knowledge structures associated with successful performance on transfer problems, and such detail is not typical of research in science education. Verbal protocols are commonly associated with "qualitative research," but they can, in fact, yield quantitative, replicable data that is useful in the investigation of knowledge structures (Robertson and Ericsson, 1988). New problems must also be used. Exactly what constitutes a transfer problem for an expert? If problems are not "typical" of the domain, are they indeed still within the domain?

Transfer across domains

The issue of transfer across domains may seem to be a dead issue. General skills may, or may not, transfer to new domains, but given the importance of domain-specific knowledge, what does it matter? Perhaps, though, it is time we looked for the transfer of something other than general skills. Perkins and Salomon (1989) refer to the process of "mindful abstraction"--a deliberate, volitional process through which a central idea, principle, rule, generalization, or strategy becomes decontextualized. Presumably, experts in a field have engaged in a process of mindful abstraction in order to generate a richly connected, hierarchical knowledge of their discipline (It is almost a sure bet that current instructional practices have done little to create that knowledge!). Does the process of mindful abstraction, rather than the abstractions themselves, transfer to new subject areas? Will a person who has learned to view the concepts and skills of physics as an integrated whole be better able to discover a similar structure for the principles of chemistry, biology, economics, or auto mechanics? I wish to point out that, by this use of the term mindful abstraction, I do not simply mean abstracting a general rule or principle for solving a class of problems, but rather the combination of many such simple abstractions to form a coherent view of a discipline. As science educators, we commonly believe in such transfer (Simon, 1980), and often use it as a justification for students learning a particular discipline. We fondly hope that, having seen the "beauty" of our particular branch of science, our students will begin to discover the coherence inherent in the world around them.

Although the transfer of the process of mindful abstraction is a worthwhile goal of science education (thus, we are searching close to where the lost keys are), research that seeks to discover how the process occurs, whether it does transfer to novel situations, and how one

can structure education to help the transfer occur, is research that explores uncharted territory (i.e., we are several block from the lamppost, and it is very dark!). Researchers in this area must begin by discovering how one comes to view a discipline as a hierarchically-structured, integrated whole. We know that many novices do not see this structure, and that many experts do see it, but we know precious little about how one gets from one stage to another.

I can suggest one possible path of investigation, and will leave it to others more clever than I to accomplish the task more simply. A longitudinal study that investigates the evolution of the knowledge structures of individuals, from novice to expert, is impractical. But one might learn a great deal from the study of individuals who have various levels of expertise in a discipline. One could arbitrarily define, say, ten levels of expertise, based on course work, research experience, teaching experience, and the like. Then one could sample a large enough group at each level to be able to extract commonalities of knowledge structures. There might, in fact, turn out to be so much variation of views of a discipline within one level, that commonalities would not exist as a workable construct. Perhaps a judicious re-definition of levels of expertise, though, would yield useful results. This proposed path is only the first step in answering the question of transfer. But once one knows something of what it means to engage in the process of mindful abstraction, determining whether that process transfers to new domains becomes a manageable task.

Summary

In this paper, I have shown that the types of problems one studies and the methodologies one uses determine how one views transfer in problem solving. Whether our inability to generalize from the simple to the complex is inherent in the subject matter (problem-solving), or whether cognitive theories are simply not sophisticated enough to allow such generalizations, remains to be seen. Until such time as the generalizations lead to consistent results, though, researchers must be cautious about making them. One way to make generalizations less suspect is to study problems that are more similar to the "real-life" problems of interest to educators. Another way is to take care in generalizing results that may be due more to the particular methodology being used than to the characteristics of the problems and problem-solvers involved in the study. I have provided two examples of how researchers in science education might move in that direction.

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Two types of transfer:

-Within a domain
-Across domains

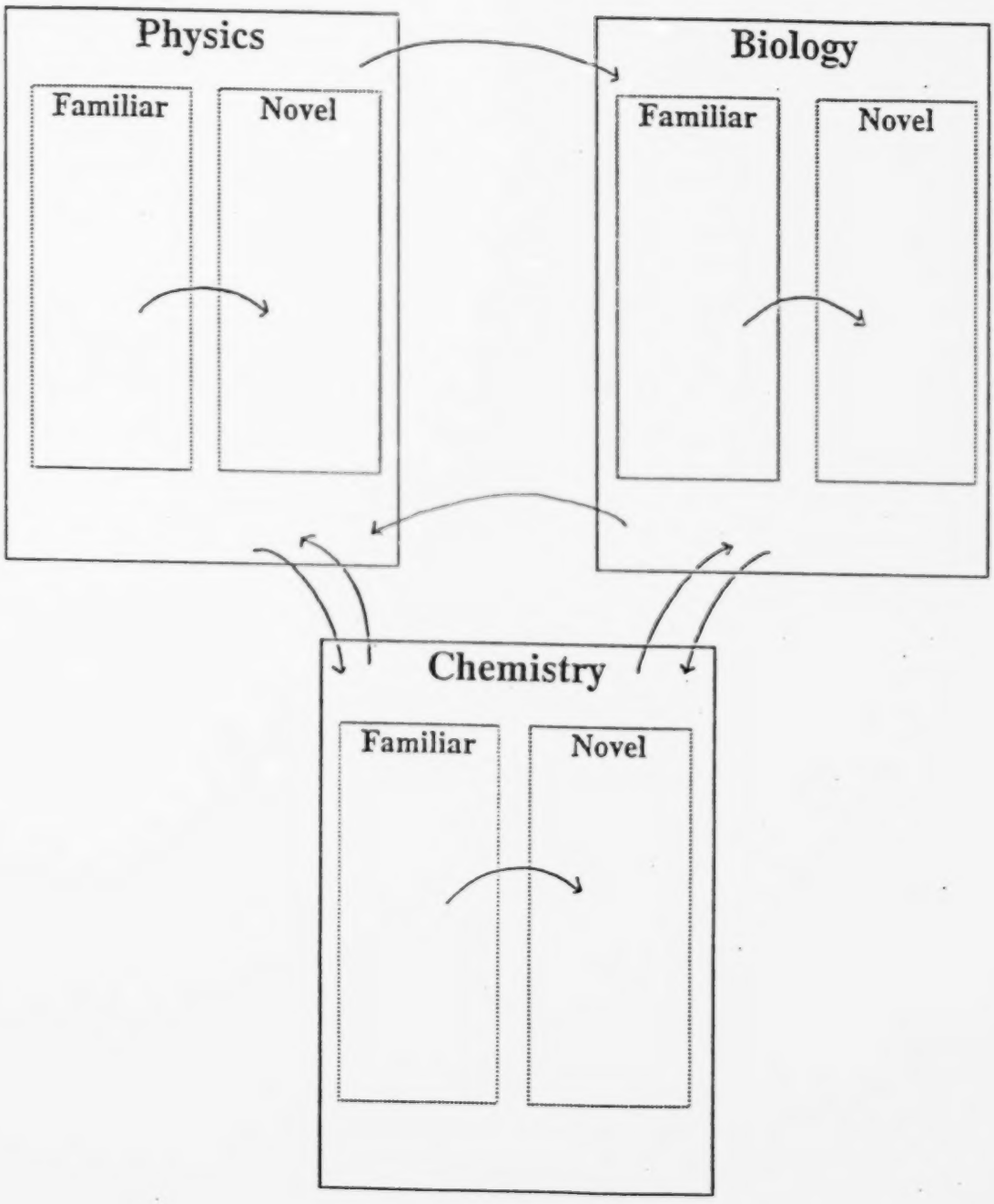

Figure 1.

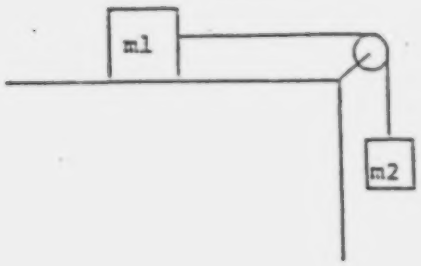

Figure 2. A mass M_1 = 5 kg is on a frictionless surface and connected to a mass M_2 = 2 kg by a massless rope which travels over a frictionless pulley as shown. What is the tension in the rope?

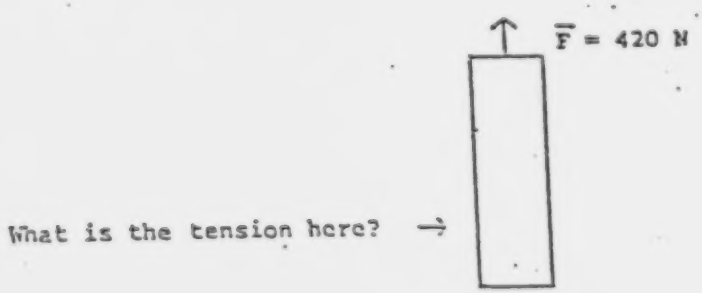

Figure 3. A heavy rope which has a uniformly distributed mass of 14 kg is being pulled upward by a force of 420 Newtons. What is the tension in the rope 3/4 of the way along its length?

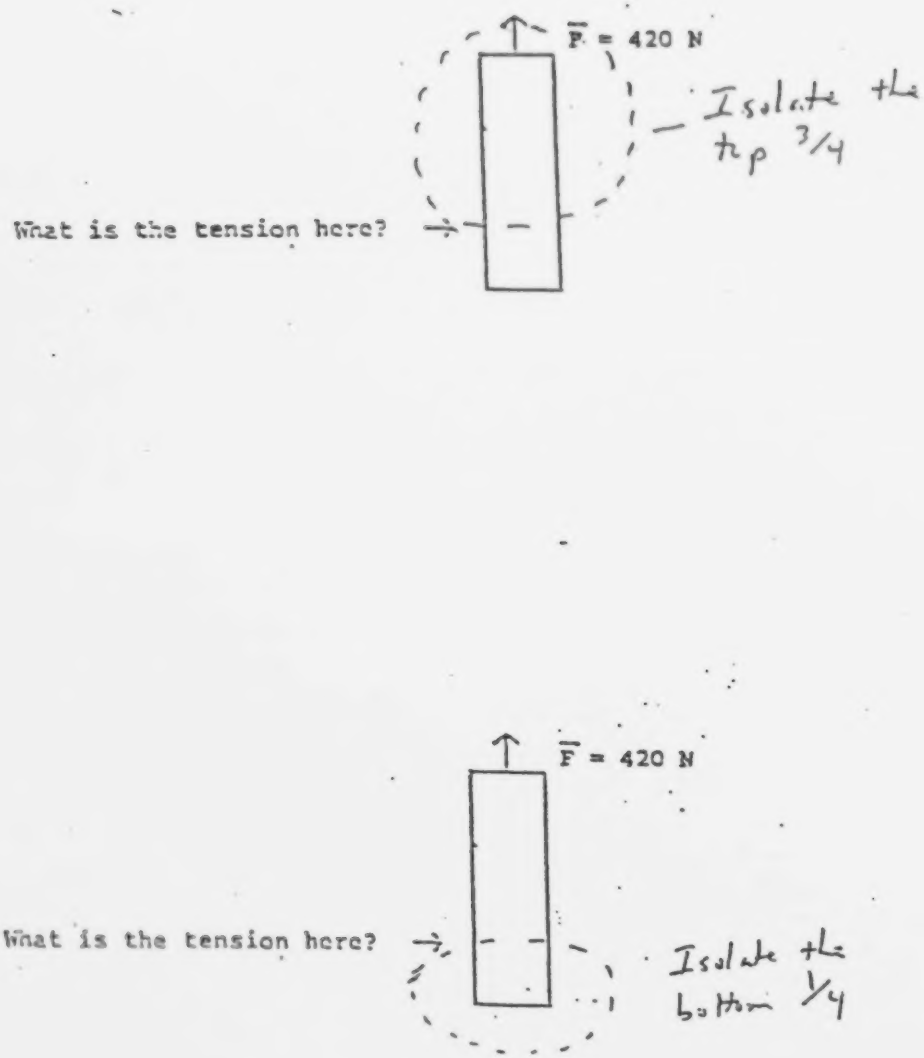

Figure 4. Two possible system choices.